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APPLICATION OF FRP FOR STRENGTHENING AND RETROFITTING OF CIVIL ENGINEERING STRUCTURES

C. SELIN RAVIKUMAR[1] & T. S. THANDAVAMOORTHY[2]

[1]Research Scholar & Assistant Professor, Dr. M. G. R. Educational and Research University, Chennai, Tamil Nadu, India

[2]Professor & Past Vice-President, Indian Concrete Institute, Adhiparasakthi Engineering College, Kancheepuram, Tamil Nadu, India

ABSTRACT

Civil engineering structures could be damaged by several causes such as earthquakes, cyclones, blast and so on. These kinds of loading either collapse the structure prematurely or cause extensive damages to it. When the damage occurs to a limited extent, it is possible to retrofit the structure. A review of the available literature has disclosed that umpteen numbers of retrofitting methodologies are available. Among them, efficient and effective method of repairing damaged structures is the application of Fiber Reinforced Plastics (FRP). In the past, several structures have been rehabilitated using the FRP techniques. This paper presents a critical review of the repairing of masonry and concrete structures using the FRP techniques and appropriate concluding remarks.

KEYWORDS: Civil Engineering Structures, Damage, Strengthening, Retrofitting, FRP

INTRODUCTION

Generally structures are subjected to geophysical and man-made loads during their service life. When the magnitude of these loads exceed the capacity or strength of the structures, they are likely to be damaged. Sometimes the strength of a structure is reduced because of the use of substandard materials in its construction or due to the application of additional load because of change in functioning or due to seismic forces for which the structure had not been designed originally. These situations warrant strengthening or up-gradation of the structure to carry the enhanced loading. Considering the economy of putting up another new structure in place of the damaged structures with the associated loss of revenue due to interruption in the functioning of the structure as well as economic and environmental factors, a decision to repair the structure becomes essential.

A variety of structural up-gradation and retrofitting techniques has been evolved over the years for different structures and also has been used. Some methods of seismic upgrading such as addition of new structural frames or shear walls have been proven to be impractical because they have been either too costly or restricted in use to certain types of structures. Other strengthening methods such as grout injection, insertion of reinforcing steel, pre-stressing, jacketing, and different surface treatments have been summarized by Hamid et al. (1994). Each of these methods involves the use of skilled labour and disrupts normal functions of the building. These well-known techniques may sometimes be inadequate for applications that should preserve architectural heritage with historical value. FRP composites are now increasingly used in the construction industry and offer considerable potential for greater use in buildings, including large primary structures. In recent years more complex applications have been developed to satisfy the desire for more dramatic features in building design.FRP composites have numerous potential advantages in building construction including the following: offsite fabrication, modular construction, reduced mass, superior durability, ability to mould complex forms, special surface finishes and effects, and improved thermal insulation and lack of cold bridging (Kendall, 2007).As a repair material also

confinement with polymeric matrix or Fiber Reinforced Plastic (FRP) composites presents significant advantages over a traditional confinement techniques: the cross sectional dimensions of the column do not increase, which permits compliance with architectural restraints; the mass of the column does not increase; which means that the seismic behaviour of the building remains unchanged (Minicelli and Tegola, 2007); the low weight of FRP materials implies that the installation procedure is faster, easier and less dangerous for the operator than implementation of traditional confining techniques, Modern techniques of confinement consist of wrapping with FRP sheets or laminates. They were introduced in engineering practice as an innovative confinement technique during the last decade as an alternative to wood or steel ties adopted in the past. Therefore the use of FRP laminates for retrofitting and strengthening is a valid alternative because of their small thickness, high strength-to- weight ratio and easeof applications.

The paper presents the application of FRP to strengthen and retrofit masonry structures, both un-reinforced as well as reinforced by reviewing critically available published literature.

Retrofitting/ Strengthening of Masonry Buildings

Masonry is one of the oldest construction technique. Many of the un-reinforced masonry (URM) buildings are historic and architectural masterpieces. They constitute a significant portion of the building inventory across the globe. Many of these buildings have been damaged by the accumulated effects of material degradation, ageing, overloading and foundation settlements, and are structurally deficient or marginal for current use. Besides these factors, change in usage and more stringent seismic design code requirements have resulted in many masonry structures that are in existence demanding retrofitting and upgrading through strengthening.Within a building, a variety of masonry structural elements are available. Among them the most important elements that are subjected to earthquake damage are the shear walls (Figure 1) which are designed to resist primarily gravity and wind loads with little or no consideration of the forces generated by the seismic event. Infill walls shown in Figure 2 are another type of masonry elements that are extensively used in old and new frame buildings. They are usually considered nonstructural elements. But under seismic action they tend to interact with the surrounding frame and may result in different desirable failure modes both to the frame and to the infill wall (Hamid et al., 2005). In general, URM structures have poor performance records even in moderate earthquakes. Their behaviour is usually brittle with little or no ductility and both structural and non-structural parts suffer various types of damages varying from invisible cracking to crushing and eventually disintegration. URM wall can fail mainly either in-plane or out-of-plane mode. Therefore investigators all over the world apply retrofitting technique to improve either in-plane or out-of-plane behaviour. Moreover introduction of reinforcement in the existing masonry to improve ductility is cumbersome and not possible without damaging it and hence the best solution of repairing is application of FRP which does not add further weight or alter the existing configuration of the structure.

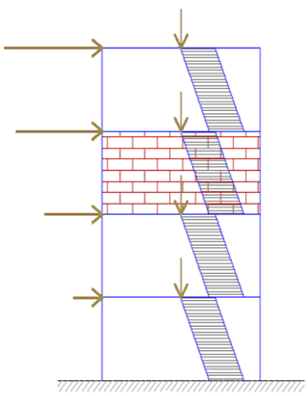

Figure 1: Shear Wall

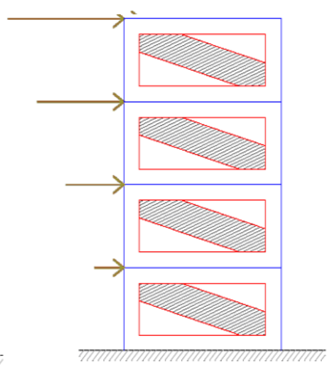

Figure 2: Infill Wall

An experimental investigation was conducted by Hamid et al. (2005) to study the in-plane behaviour of face shell mortar bedded URM wall assemblages retrofitted with FRP laminates. Forty two URM assemblages were tested under different stress conditions present in masonry shear and infill walls. Tests included prisms loaded in compression with different bed joint orientation (on/off-axis compression), diagonal tension specimens, loaded under joint shear. The behaviour of each specimen type is discussed with emphasis on modes of failure, strength and deformation characteristics. Results showed that the application of FRP laminates on URM has a great influence on strength, post peak behaviour, as well as altering failure modes and maintaining the specimen integrity. The retrofitted specimens reached compressive strength of 1.62-5.64 times that of their un-retrofitted counterparts, depending on the bed joints orientation, and joint shear strength increased by eight fold.

An experimental programme conducted at the University of Alberta, Canada showed that externally applied FRPs are effective in increasing the load carrying capacity of URM walls that are subjected to out-of-plane flexural loads. (Albert et al.,2001). In this investigation a number of different FRP materials, viz., carbon plates, carbon sheets, and glass sheets were used. Tests conducted on FRP coupon specimens prepared in accordance with ASTM D 3039M (ASTM, 1995) has disclosed that there is a wide variety of strength as well as stiffness associated with the different failures. The carbon strap has the highest strength and stiffness results but also the most expensive. The glass sheet has the lowest strength and stiffness and is the cheapest. The carbon sheet is moderately priced and has moderate properties.Overall results show that strength and ductility of the specimen is increased significantly when strengthened with FRP. The load mid-span deflection response for all strengthened and tested specimens is typically represented in Figure 3.

It can be characterized by separating it in to two phases. The first phase is non-linear and represents the stiffness contribution of the masonry materials. The second phase is linear and represents the stiffness contribution from the FRP reinforcement.

For the retrofitting of the civil infrastructures, an alternative to FRP externally bonded laminates is the use of near surface mounted (NSM) FRP bars. This technique consists of placing a bar in a groove cut into the surface of the member being strengthened. The FRP bar may be embedded in an epoxy- or cementitious- based paste, which transfers stresses between the substrate and the bar (Figure 4). The successful use of NSM FRP bars in the strengthening of concrete members has been extended to URM walls.

Tumialan et al. (2002) have described three applications of FRP bars for the strengthening of URM and present experimental result obtained from the investigation. In the first application, FRP bars are applied vertically to resist out-of-plane forces acting on the masonry walls, i.e., flexural strengthening. In the second application, bars are inserted horizontally in the masonry joints to strengthening the wall where subjected to in-plane forces, i.e., shear strengthening. Finally, the third application dealing with the retrofitting of masonry walls showing deficient anchorage to the base beam. In this application, FRP bars are placed in the toe region of the wall acting as anchors to increase the flexural capacity.

According to the authors masonry walls strengthened with NSM FRP bars exhibited performance identical to that strengthened with FRP laminates.It has been claimed that flexural strengthening with NSM FRP bar could increase the masonry capacity ranging from 4 times to 14 times than that of the original capacity. Similarly, it has also been claimed that the shear capacity can increase from 30 % to 80 % of the original value. The use of NSM FRP bars is attractive, since their application does not require any surface preparation work and requires minimal installation time.

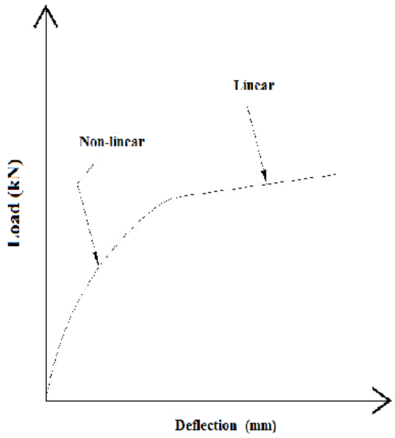

Figure 3: Typical Load-Deflection Behaviour of FRP Strengthened Specimen

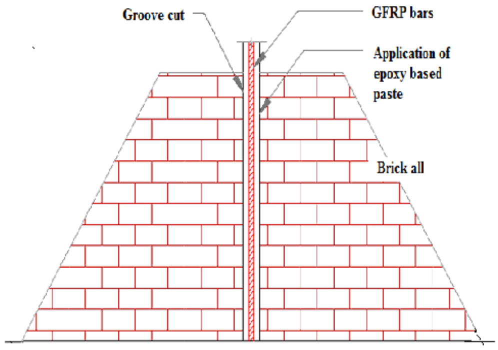

Figure 4: NSM FRP

Concrete Masonry Walls

Masonry has been used as a common construction material world-wide for many countries. However, the vulnerability of un-reinforced systems was highlighted during the occurrences of earthquake. As a result, reinforcement was introduced to masonry shear walls to resist lateral forces generated in regions of high seismic activity. These walls are usually subjected to simultaneously gravity and lateral loads, resulting in overturning moments during seismic excitation. Depending on the load condition, the amount of longitudinal and shear reinforcement, and the aspect ratio, two types of failure mechanisms can be identified in masonry shear wall panels. One is a flexural type of failure characterized mostly by the tensile yielding of vertical reinforcement or crushing of masonry at critical wall sections. The second type is a shear failure manifested by diagonal tensile cracking. While a flexural tensile failure mode is ductile and a preferable mode, a shear mode failure is brittle in nature and may lead to catastrophic failure of the masonry. In order to prevent such catastrophic failure, New-Zealand was amongst the first countries to develop reinforced masonry seismic design procedure based on the principle of capacity design that required the dependable shear strength to exceed the maximum lateral loading necessary to develop the wall flexural over strength (Voon andIngham, 2006).

According to Tomazevic and Weiss (1994) by reinforcing the masonry walls with vertical reinforcement at the borders of the walls and horizontal reinforcement in the mortar bed joints, the lateral resistance, energy-dissipation capacity, and global ductility of the building was significantly improved.

Concrete masonry units (CMUs), commonly known as concrete blocks, are often used in the construction of exterior wall panels of structures. These walls may become a debris hazard to building occupants where high explosives, e.g., a terrorist vehicle bomb, are detonated outside of a building (Baylot et al., 2005).

Most buildings in existence now have not been designed to withstand blast loading. The resistance of a wall to blast loads can be augmented by increasing the mass and ductility of the wall with additional concrete and steel reinforcement, which can be time consuming and expensive. For this reason among others, a need has arisen for cost effective methods of reinforcing existing concrete and masonry walls, over the past decade, the U.S. Department of Defense has encouraged and sponsored research toward developing methods of reinforcing structures to protect building occupants from the effects of external explosion. The focus of research on wall reinforcement has shifted recently from applying stiff fiber-reinforced composites to using lower-strength, higher- elongation elastometric polymers that can be easily applied to the wall interior. Davidson et al. (2005) have presented recent efforts that have demonstrated an

innovative use of thin-membrane elastomeric polymers to prevent breaching and collapse of URM walls subjected to blasting.

Since 1995, the Air Force Research Laboratory (AFRL) at Tyndall Air Force Base, Florida, has conducted research toward developing lightweight, expedient methods of retrofit strengthening structures for blast loading. A wide range of potential external reinforcement materials, including Carbon and Glass fiber-reinforced composites, aramid and geo-textile fabrics, etc., were investigated by AFRL engineers and other agencies involved in the developments of blast reinforcement technology.

In 1999, AFRL began experimenting with other classes of "neat" (no failure reinforcement) polymer. A total of 21 prospective polymers were evaluated in the initial phases of the project (Davidson et al., 2005). Seven of the materials were extruded thermoplastic sheet materials, 13 were spray-on polymer, and one was a brush on polymer. Mechanical properties were evaluated for all the extruded polymers. The extruded thermoplastics were stiffer and stronger with secant modulus 113 MPa and maximum tensile strength 55.80 MPa than the other classes of materials. However extruded thermoplastics are not suitable for large-scale applications due to the challenges of extrusion. The brush-on polymer is weak, brittle and requires long cure times. The 13 spray-on polymers were comprised of seven polyurethanes, one polyurea, and five polyurea/ urethanes. The polymers have fast gel and cure times, making application to vertical and overhead surfaces feasible. The polyurea are typically stiffer than polyurethanes but have less elongation capacity. As a result, urethanes are often combined with ureas to increase elongation capacity.

Davidson et al. (2005) have discussed the damage and failure mechanism observed from 12 polymeric reinforced masonry walls during explosive tests designed to establish the limits of blast resistance effectiveness of polymeric reinforced walls.

The masonry wall tests conducted by Air Force Research Laboratory at Tyndall (AFRL)indicate that a paint-on polymeric reinforcement approach can be effective in reducing the vulnerability of un-reinforcement non-load bearing CMU walls subjected to blast loading.

Kuzik et al. (2003) have investigated the out-of-plane flexural behaviour of masonry walls reinforced externally with glass fibre reinforced polymer (GFRP) sheets and subjected to cyclic loading. A full-scale test programme consisting of eight wall specimens was conducted. The authors have observed that the overall flexural performance of the masonry walls reinforced externally with GFRP sheets was excellent. Except for visible cracks, the walls maintained their structural integrity throughout the out-of-plane cyclic loading. The integrity of the GFRP sheets/ masonry wall system is maintained through the load versus deflection hysteretic responses. The unloading/reloading paths for successive loading cycles were similar, indicating little degradation. Besides, all of the unloading paths part near the origin result in a pinching effect. Thus, the general behaviour of the walls was very predictable.

The behaviour of seven half scale masonry specimens before and after retrofitting using FRP was investigated by El Gawady et al. (2007). Four walls were built using half scale hollow clay masonry units and weak mortar to simulate walls built in central Europe in the middle of the 20th century. There walls were first tested as URM walls, then the seismically damaged specimens were retrofitted. The fourth wall was directly upgraded after construction.

The retrofitting and upgrading was carried out using FRPs with different axial rigidity. The FRP was applied on the entire surface of a single-side of each test specimen. All the specimens were tested under constant gravity load and incrementally increasing in-planeloading cycles.

It has been observed by the authors that FRPs improved the lateral resistance of specimens by a factor of 1.4 to 5.9. Further the increase in the lateral strength was approximately increased proportional to the amount of the axial rigidity of FRP. By using FRP retrofitting, the cracking load and pattern are effectively controlled. The mode of failure was found to be strongly dependent on the axial rigidity of FRP. Higher axial rigidity of FRP led to very ductile failure, Moreover the energy dissipation of the retrofitting and upgraded specimens was higher than the control specimens. However, most of this energy dissipated due to friction in the masonry rather than due to deformations in the FRP. The role of the FRP was to keep the masonry together even at high drifts. .

Strengthening of Masonry Vaults

Among the structural components in masonry buildings such as arches and vaults deserve particular attention. They are very widespread in European historical centers, and their preservation as part of the cultural heritage is a topical subject. Because of their ages or for accidental causes such as earthquakes, these structures can suffer several type of damage, so the contribution of strengthening materials and repair techniques may be required to reestablish their performances and to prevent the brittle collapse of the masonry in possible future hazardous conditions.Recently the University of Padova has started experimental research to study the behaviour of masonry vaults strengthened by Carbon FRPs (CFRPs) or glass FRPs (GFRPs) placed at the intrados or at the extrados of the structure. A multilayer system of adhesion based on epoxy adhesives and designed to provide a support as homogeneous as possible for the failure has been adopted.

The results of experimental research on brick, masonry vaults strengthened at their extrados or at their intrados by FRP strips are presented by Valluzzi et al. (2001). Six masonry vaults strengthened by glass FRPs or Corbon FRPs have been tested. Different kinds of failure mechanisms have been observed. The width and the stiffness of the strips seem to have a strong influence on the behaviour in proximity to the failure. Regardless of the type of strengthened material, vaults strengthened at the extrados revealed a possible brittle mechanism of failure due to the sliding between mortar and bricks. Such a mechanism can be prevented by placing a proper amount of fiber distributed in the springer zones.

Because of the larger surfaces available for the adhesion, higher value of ultimate strength of the vaults has been detected for the fibres with lower mechanical characteristics. Vaults strengthened at their intrados revealed a more ductile mechanism of failure because of the attachment of the fibers perpendicularly to the masonry interface. The failure is located in a limited zone, so the binding action of the strips can still avoid the collapse of the structures.

CASE STUDIES

Fibre Wrapping of Corporation Building and Bridge

The Chennai Corporation in Tamil Nadu, India used fibre wrap technology to fortify its old civic structures, including buildings and bridges, against earthquakes. The fortification techniques have been initiated in the wake of the city being upgraded to seismic zone III a few years ago. Work on Kodambakkam Bridge and Ripon Buildings of more than 150 years old has already been started.

According to Lopez (2003) over 1500 m^2 of fibre wrap was being used for strengthening columns of the ground floor of Ripon Buildings. This would strengthen the columns that are likely to be damaged during seismic events. The fibre wrap being used now was capable of withstanding extremes of temperature. It was also cheaper than other available technologies. The fibre wrap was wound around the columns and the original material (lime mortar or cement) will then be packed on top of it (Figure 5).

The civic body had also done fibre wrapping on the columns of Kodambakkam bridge as part of restoration of the 50-year-old structure. The restoration would include spraying of anti-corrosion material and grouting. A few years ago, an expert study conducted on the 623-metre-long and 12.8-metre-wide structure concluded that it had weakened.

As per a survey conducted by the Corporation some of the Corporation's office, residential and commercial buildings too have been declared weak. The authorities of the Corporation were of the opinion that use of fibre wrap would strengthen such structures and prevent them from collapsing during, or after a seismic event.

Figure 5: Fibre Wrapping of Chennai Corporation Building

Retrofitting of a Medieval Bell Tower with FRP

It is a common practice in structural engineering to retrofit existing structures to resist seismic actions that they were not originally designed for. Seismic retrofitting of monument structures requires compliance with restrictive constraints related to the preservation of original artistic and structural features. Any intervention that is conceived must achieve structural performance and at the same time comply with the appearance and structural mechanism of the original and be as minimally invasive as possible. The intervention on the bell tower of Santa Lucias Church in Serra San Quirico, Ancona, Italy is an application of composite materials for the seismic retrofit of historic monuments where traditional retrofit strategies are not suitable. Cosenzo and Iervolino (2007) have presented a case study of retrofitting of the medieval bell tower in Serra San Quirico using the FRP.

Affected by the Umbria-Marche earthquake in 1997, the bell tower of Santa Lucias Church is a multilayered masonry structure built in the 15th century. It is located at the centre of the little town of Serra San Quirico, a medieval suburb near Ancona, and is surrounded by many residential constructions of the same age.

It is a calcareous masonry building about 30 m in height and 1,200 m in width with a rectangular plan view (Figure 6).Because of damage and failure of similar structures in the same area, a desire to improve the seismic capacity of the tower was expressed by the local Architectural Heritage Supervision Office. Initially, to fulfill the scope of retrofitting an intervention based on steel reticular system anchored to the inner side of the tower was proposed.

The Architectural Heritage Authority recognized that this intervention violates the above described principles and, therefore, rejected it.Moreover, considering the steps and projections in the masonry walls and their lengths, a solution based on jacketing repair or steel plate repair also cannot be successful and may defeat the very purpose of the monumental structure.

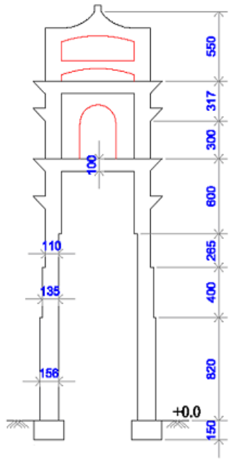

Figure 6: Cross-Section of Bell Tower

Subsequently FRP intervention was proposed, designed, approved and installed. The design also included finite element simulation and a site structural assessment. Effectiveness of the intervention was evaluated by performing a nonlinear static analysis, i.e., push over analysis, both on retrofitted and original structures and by comparing the results. Pushover curves for the retrofitted and un-retrofitted structures are shown in Figure 7.The FRP intervention enhances the seismic capacity of the structure and is fully provisional as it may be removed by heating the FRP with a hot air jet.

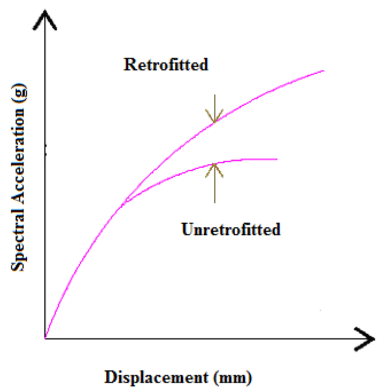

Figure 7: Comparison of Push over Curves of Retrofitted and Unretrofitted Structures

Underwater Pre-stressed Piles Repair using FRP

Mullians et al. (2005) have described a field demonstration study to evaluate the application of FRP for the underwater repair of corroding pre-stressed piles. A total of four full sized 350 mm x 350 mm square pre-stressed piles were wrapped, two with carbon and two with glass. Two of these wrapped piles, i.e., one carbon and one glass, were instrumented to allow evaluation of their post wrap performance. Two other unwrapped piles serve as controls. Instrumentation allowed determination of the corrosion potential over the unwrapped surface and the corrosion rate for the wrapped piles.

The study showed that underwater wrapping is a visible system. As with most FRP retrofits, surface preparation is of paramount importance. In this case, surface preparation required equipment capable of operation underwater to grind sharp corners. Although initial field tests on the wrapped piles indicated that the bond between the wet concrete and the FRP was relatively poor, laboratory tests showed the bond was adequate to restore the full undamaged capacity. Corrosion rate measurements indicate that the performance of the wrapped piles is consistently better than the unwrapped controls. The underwater wrap used a unique water activated urethane resin system that eliminated the need for cofferdam

construction. The preliminary findings are quite encouraging and suggest that underwater wrapping without cofferdam construction may provide a cost-effective solution for pile repair. In this case, description about the treatment of corrosion is hardly presented.Of course, there is no doubt wrapping may prevent ingress of marine products.But the existing corrosion products still remain inside and proliferated with the passage time.

Retrofitting of Hollow Bridge Piers

In order to maximize efficiency in terms of the strength-to-mass and stiffness-to-mass ratios and to reduce the mass contribution of the pier-to-seismic response, it has been a common engineering practice to use hollow sections for bridge piers particularly for tall piers. Hollow bridge piers are currently being used in high speed rail and highway projects in Taiwan. Recent earthquakes such as the Northridge earthquakes of 1994, the Kobe earthquake of 1995, and the Taiwan earthquakes of 1999, have respectively demonstrated the vulnerabilities of older reinforced concrete piers to seismic deformation demands and shear strength. Yeh and Mo (2005) have presented the results of an investigation on hollow piers retrofitted with carbon fiber reinforced polymer (CFRP) sheets. In their investigation the authors have tested circular and rectangular hollow bridge piers retrofitted by CFRP sheets under a constant axial load and a cyclic reversed horizontal load to study the seismic behaviour, including flexural ductility, dissipated energy and shear capacity. An analytical model was also developed to predict the moment-curvature relationship of sections and the lateral load displacement relationship of piers. The test results are also compared with the proposed analytical model. It was found that the ductility factor of the tested piers ranged from 3.3 to 5.5 and that the proposed analytical model could predict the lateral load displacement relationship of such piers with reasonable accuracy. All in all, CFRP sheets can effectively improve both the ductility factor and the shear capacity of hollow bridge piers. Here the retrofitting could have been carried out using jacketing technique. But such a solution would have increased the size of the piers which may affect the flow in the water course.

Strengthening of R.C. Beam-Column Joints with FRP

Recent earthquakes worldwide have illustrated the vulnerability of existing reinforced concrete (RC) beam-column joints to seismic loading. Strengthening of R.C. joints is a challenging task that poses major practical difficulties. A variety of techniques applicable to concrete elements have also been applied to joints with the most common ones being the construction of RC or steel jackets. However, these techniques have inherent limitation in the form of intensive labour and artful detailing. In the case of concrete solutions there is a possibility of dimensions and weights of the elements being increased.

New technique for repairing structural elements is now available. This technique involves the use of FRP as externally bonded reinforcement (EBR) in critical regions of RC elements. FRP materials, which are available today in the form of strips or in situ resin impregnated sheets, are used to strengthen a variety of RC elements, including beams, slabs, columns, and shear walls, to enhance the flexural, shear, and axial capacity of such elements.

The results of a comprehensive experimental programme aimed at providing a basic understanding of the behaviour of shear-critical RC joints strengthened with FRP under simulated seismic load have been presented by Antonopoulos and Triantafillou (2003). The role of various parameters such as area fraction of FRP; distribution of FRP between the beam and the columns; axial load of column; steel reinforcement in internal joint; initial damage; carbon versus glass failures; sheet versus strips; and effect of transverse beams, on the effective FRP has been examined through 2/3 scale testing of 18 exterior RC joints.

The tests performance in this study demonstrated that externally bonded FRP reinforcement is a viable solution towards enhancing the strength, energy dissipation, and stiffness characteristics of poorly detailed RC Joints in shear that

are subjected to simulated seismic loads. Relatively low fraction of FRP area enhanced both the peak lateral load capacity and the cumulative dissipated energy up to about 70 to 80 percent. The increase in stiffness varied with the imposed displacement level reached values in the order of 100 percent. The results demonstrate the important role of mechanical anchorages in limiting premature de-bonding. Considering the problems associated with the repairing of RC joints with conventional techniques the FRP intervention is the apt solution with minimum disturbance.

Concrete Confined with FRP Tubes

Axial load on concrete causes the concrete to expand laterally. In an encased concrete column, this lateral expansion is resisted by the hoop action of the shell that surrounds the concrete. Such confinement changes the stress-strain behaviour of concrete and also increases its compressive strength as in Figure 7 which depicts the typical stress-strain relationship of un-confined concrete, confined by FRP tube and by a steel tube respectively.

The advantage of improved performance of concrete encased in steel tubes has been well recognized for a long time and is used in structural applications (Choi and Xiao, 2010). However, the use of FRP tubes to encase concrete columns instead of steel is a more recent development that offers certain advantages, such as elimination of corrosion of the confining tube. FRP tubes are also light-weight and easy to handle. They act as an ideal formwork that eventually remains in place as permanent part of the structure. The confining pressure of an FRP shell subjects the core concrete to a tri-axial state of stress. Concrete itself prevents the shell from buckling inward. The shell protects the concrete surface from physical damage and environmental effects such as carbonation and chloride penetration. The shell acts as a uniform longitudinal reinforcement located at the most advantaged position to resist moments. Therefore, concrete confined with FRP is currently considered a technically attractive system for piles, highway overhead signs, and other compression members that can be subjected to moments.

Bacque et al. (2003) have developed analytical models for prediction of stress-strain curves for concrete confined with FRP. The predicted stress-strain curves for confined concrete using the proposed models were compared with those of tests on concrete specimens confined with FRP. The agreement was found to be good. The proposed model was also able to predict the well-known behaviour that concrete confined with a GFRP exhibits better ductility as compared with concrete confined with CFRP.

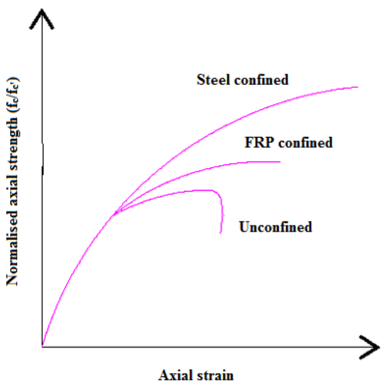

Figure 8: Typical Effect of Confinement of Column

FRP tubes are relatively flexible when compared to steel tubes. This will permit to some extent bulging of concrete core under axial loading. In this situation when bulging becomes excessive, it will rupture the FRP tube longitudinally. It seems the authors have hardly considered this aspect in their analysis.

CONCLUDING REMARKS

FRP as strengthening and retrofitting material has several advantages over conventional materials. Its thickness is small and hence its application does not add weight to existing structures. It helps to preserve the cultural heritage of monumental structures. It is not corrodable.

It has been established through experimental testing that the compressive strength of URM walls retrofitted using FRP laminates had increased by 1.62 – 5.64 times that of un-retrofitted counterparts. Similarly, the joint shear strength increased eight fold.

NSM FRP bar application has been found to be very promising. It has been reported that flexural capacities NSM FRP retrofitted masonry had increased by 4 to 14 times of the original capacity and the shear capacity from 30 to 80 percent.

Air Force Research Laboratory at Tyndall has reported that paint on polymeric approach can effectively reduce the vulnerability of un-reinforced non-load bearing CMU walls subjected to blast loading.

In a case study of bell tower repair it has been shown that FRP intervention enhanced its seismic capacity and such a solution was acceptable to local Architectural Heritage Authorities.

In a case study of prestressed pile repair, it was observed that underwater FRP wrappings without cofferdam construction could provide a cost effective solution for pile repair.

In the case of study of repairing of hollow bridge piers, CFRP sheets can effectively improve its ductility factor and the shear capacity of hollow bridge piers. It was found that the ductility factor of tested piers ranged from 3.3 to 5.5.

It has been demonstrated by experimental investigation that externally bonded FRP reinforcement is a viable solution towards enhancing the strength, energy absorption and stiffness characteristics of poorly detailed RC joints in shear.

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